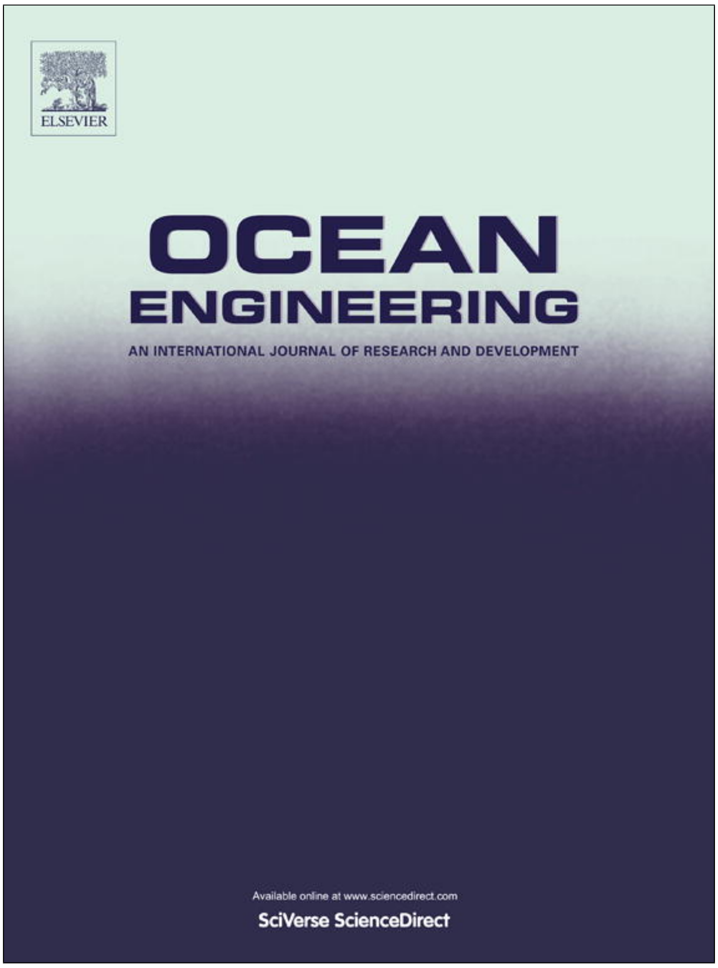

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Ocean Engineering 54 (2012) 34–45

Contents lists available at SciVerse ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Numerical optimization of trawl energy efficiency taking into account fish distribution

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ARTICLE INFO

Article history:
Received 4 February 2011
Accepted 1 July 2012

Keywords:
Fishing gear
Bottom trawl
Modeling
Optimization
Fuel consumption
Drag
Swept area
Fish distribution

ABSTRACT

This study reports on energy efficiency optimization regarding bottom trawls. Efficient fishing gear uses up only a small amount of energy per fish caught. Drag and mouth area during trawling operations affect energy efficiency. Drag causes the energy consumption and the trawl mouth area impacts the quantity of fish caught, hence an energy efficient gear has a low ratio drag on the mouth area. A novel numerical optimization technique using spatial fish distribution is presented in this work. The tool is based on a FEM mechanical model for trawls which consist mostly of netting panels sewn together. This tool is adapted to minimize an objective function namely the drag-to-mouth area ratio. This technique consists in modifying the design of all the panels of the trawl. In this paper the modifications are constant and quantified in terms of mesh number. Moreover the trawl mouth area takes into account the presence of fish within a given depth with respect to sea bottom and the value of the depth is adapted to the fish species of interest. Trawl design optimization with two uniform fish distributions at a given depth (6 m and 3 m above the sea bed) and one linear distribution at 6 m above the sea bed are compared. The application of this tool when designing a bottom trawl for research vessels leads to an energy economy ranging from 16% to 52% under certain assumptions.

1. Introduction

Fuel consumption in the fishing industry is a major issue regarding environmental effects and is a burden on general cost.

In some cases, the energy budget could well reach up 30% of the turnover. A cost of this magnitude hitting fishing businesses is negative as such dependence does not make them viable, especially when the energy costs are so volatile.

The ratio between the energy consumed per caught fish is usually considered as a way of measuring such a dependency on energy in the fishing industry. The ratio mean value is around 0.6 l/kg (Tyedmers et al., 2005), but could vary between 0.1 and 3 l/kg depending on the species and fishing techniques.

An issue relating to this matter is the sustainability of seafood production and consumption. In this respect, the work of Schau et al. (2009) represents a Norwegian approach to this problem. They suggest possible means for reducing energy use and greenhouse gas emissions based on changing operational strategies, hull shapes or the introduction of alternative energy sources. On the other hand, a Danish study (Bastardie et al., 2010) focuses on the modification of the allocation of fishing effort due to the increase in energy cost. This study uses modeling and finds that the fishermen are expected to:

(i) reduce the distance between the harbor and the fishing grounds,
(ii) use alternative (closer) locations for fish landing,
(iii) optimize the trip length.

An improvement in energy efficiency could be carried out by using a different technique: Macdonald et al. (2007) have compared jig fishing to trawling. Thomsen (2005) has shown that ships converted from single trawling to pair trawling saved 40–45% fuel. Rihan (2005) suggests turning back to traditional single rig trawling from twin rigs in order to decrease fuel consumption.

An improvement in fuel dependency could also be achieved by modifying fishing gears to render them more fuel efficient. Kim et al. (2007) approached this problem from the angle of hydrodynamic resistance by developing a new approach to the analysis of fishing gear performance using computer simulations. He simulated modifications to the gear such as decreasing twine diameter or increasing mesh size in order to assess the impact of these modifications on fuel consumption.

Since one of the main fishing gears used in Europe is the trawl, numerous studies have been dedicated to this fishing technique. Optimization could be reached as Kim et al. (2007) suggested, by

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http://dx.doi.org/10.1016/j.oceaneng.2012.07.014

reducing the twine diameter or increasing mesh sizes whenever possible (Ward et al., 2005), modifying trawl design (Parente et al., 2008), or finally modifying the otter board design (Ivanovic and Neilson, 2010; Sterling and Eayrs, 2010).

The method described in this paper is based on numerical modeling for netting structures. Few numerical models devoted to structures made of netting have been developed. Bessonneau and Marichal (1998), Niedzwiedz (2001), Lee et al. (2004) and Tsukrov et al. (2003) have developed 3D numerical methods which describe twines of the net by numerical bars. These methods take into account a large number of twines in each numerical bar. The forces considered are the drag due to the water flow, but also the weight and buoyancy of the net. Some of these methods take into account twine elasticity. An iterative method gives equilibrium to the net. The drawback of these models is that the numerical bars must be parallel to the actual twines of the netting, which means that the model user is not free to create the numerical bars. To avoid the problem of constrained numerical elements, the present paper is based on a finite element method (FEM) model for netting using a triangular element (Priour, 1999, 2005).

The present paper describes an automatic optimization procedure for bottom trawl panel cutting in order to decrease a given objective function. The latter is designed in order to assess the fuel consumed per fish caught. It is based on a combination of the geometrical and mechanical finite element method model adapted to fishing net structures, which has been described in Priour (1999, 2005). It uses a constrained optimization tool that starts from a reference model and selects the best result among several others modified by objective function minimization. Thanks to this study we demonstrate that this tool offers potential savings in fuel consumption and could lead to a moderate increase in catch volume which, in turn, is mitigated by a decrease in the number of fishing trips.

This study focuses exclusively on trawl design, which means we have excluded an analysis on vessel or door modifications, even though it is quite clear that substantial modifications in the trawl could lead to wide-ranging modifications in the drag which means that the door area must also be altered.

2. Method

2.1. Description of the optimization method

Optimization is based on three main points.

The first one is the objective function definition. It is expected to decrease during the optimization process. In the present study the objective function represents the quantity of fuel consumed with respect to the quantity of caught fish. It will be shown later in the paper that the objective function is a scalar, equal to the ratio of the trawl drag to the mouth area encountering fish distribution.

The second one is the list of variables. It is represented by a vector which contains all the variables. In the present paper this vector describes the design of the trawl. Figs. 1 and 2 show an example of the link between this vector and the design. The aim of the optimization method is to find the best variables, or in other words, the variables that lead to the minimum value of the objective function.

The third one, which is not always present in optimization, is a list of constraints. They consist of tests that might lead to a rejection of some values of the variables. In the present paper one constraint is that the headline must always be in front of the foot-rope to avoid fish escapement. The second constraint is that the foot-rope must always be in contact with the sea bottom. These constraints are translated into scalars which are compared to the corresponding boundaries.

This method requires a tool that is able to evaluate the objective function from a vector set of variables. This tool is the finite element method (FEM) implementation of the mechanical model (Priour, 1999, 2005) adapted to this optimization.

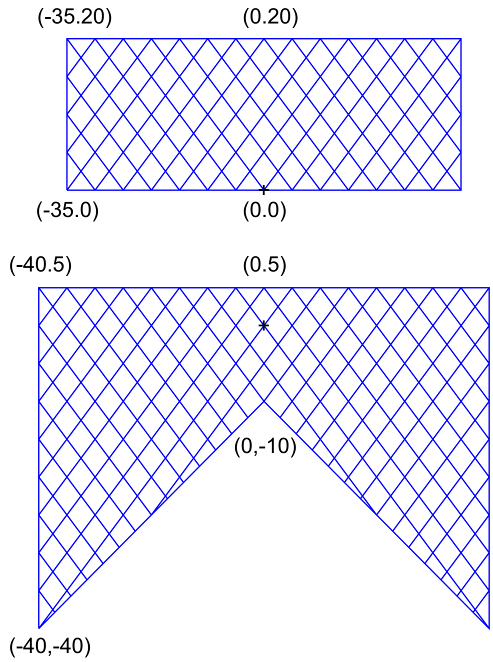

Fig. 1. Layout of a simple symmetrical structure with two netting panels having eight nodes on one side of the symmetry plan defining the whole structure. The mesh coordinates of the first panel (bottom) and the second one are noted. This design is quantified by $U_0=[-40\ -40\ -40\ 5\ 0\ 5\ 0\ -10\ -35\ 0\ -35\ 20\ 0\ 20\ 0\ 0]$. The first nodes of the two panels are bottom left and the numbering is clockwise. Only one twine out of five is drawn. Origins of mesh coordinates are highlighted.

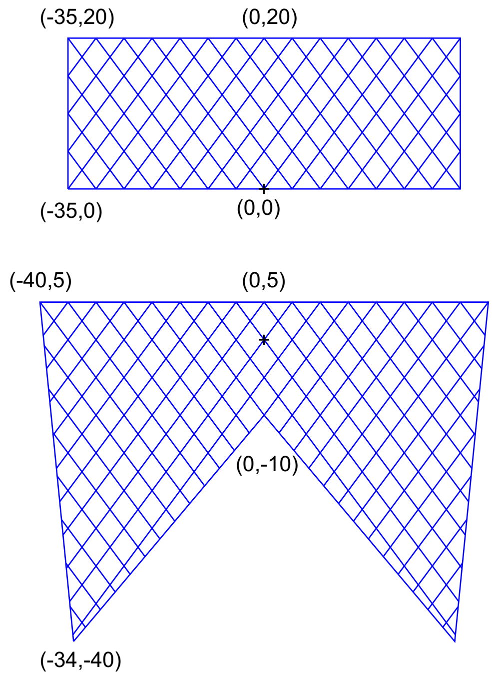

Fig. 2. Appearance of the structure after a modification of the first node in terms of horizontal number of meshes along the positive direction. The design of this structure is quantified by $U_1=[-34\ -40\ -40\ 5\ 0\ 5\ 0\ -10\ -35\ 0\ -35\ 20\ 0\ 20\ 0\ 0]$.

To run the optimization method, we must, first of all, initialize all the variables (node coordinates of the net panels) according to a reference trawl. It will be shown that in trawl optimization the number of variables is quite large (134 for Fig. 5) which is computationally intensive. The optimization method could be best described by the following pseudo-code:

```
for i=1 to panels_nb
  for j=1 to panel(i).nodes_nb
    if node(j) does not belong the symmetry plane
normal to x axis then
      change node(j).x by +panel(i).delta_x;
      evaluate OF;
      change node(j).x by -panel(i).delta_x;
      evaluate OF;
    endif
    if node(j) does not belong the symmetry plane
normal to y axis then
      change node(j).y by +panel(i).delta_y;
      evaluate OF;
      change node(j).y by -panel(i).delta_y;
      evaluate OF;
    endif
  endfor;
endfor;
select node change giving largest decrease of OF;
pick corresponding node coordinate in case new OF
 <old OF;
modify trawl design;
```

where *panels_nb* represents the number of net panels, *panel*(*i*).*nodes_nb* represents the total number of nodes in panel *i*, *node*(*j*).*x* represents the horizontal coordinate in node *j*, expressed in the number of meshes, *panel*(*i*).*delta_x* represents the modification change horizontally in mesh number of panel *i* and *panel*(*i*).*delta_y* is its modification change vertically in mesh number, and OF the objective function.

In other words, in order to perform such optimization we must start from reference values and perform the following tasks:

(i) impose small modifications to the variables separately (one by one),
(ii) calculate the objective function after each modification,
(ii) select variables leading to the best objective function while respecting imposed constraints.

These three steps are repeated starting from the new variables until no improvement is observed in the objective function. Such a process ensures convergence: the new variables are chosen only if the objective is improved.

The efficiency of the method depends strongly on the amount of modifications in the variables. This modification is a percentage of the netting panel size of the trawl. As an example a modification of 4% of a panel consisting of one hundred meshes will be a modification of exactly four meshes. Fig. 2 presents an example of modification of 7.5% relatively to Fig. 1, because the modification is six meshes for a panel of 80 meshes large.

The optimization procedure which we called SOT (successive optimization tool) is amply described in Priour (2009) and Priour and Khaled (2009). Nonetheless the objective function used in the case of bottom trawl was the drag over the trawl swept width. Using this approach for a bottom trawl as in Khaled and Priour (2010), we found that the vertical opening of the optimized trawl was too small resulting in a potential decrease in the amount of fish caught. This prompted us to amend the SOT optimization method by considering an alternative objective function given by the ratio of the drag to the effective swept area. The latter is given by the intersection area between the trawl mouth and the volume over which the fish population is distributed.

2.2. The optimization objective

The energy required annually during the hauls is due to the drag (D) and the annual distance of the hauls (L). If we accept that the efficiency of the propulsion system is known (η) as well as the work capacity of the fuel (h_f), the fuel volume of the trawling operation (V_f) can be assessed by the following equation:

$$V_f = \frac{DL}{\eta h_f} \tag{1}$$

V_f is the fuel volume used per year (m^3), D is the drag of the gear (N), L is the towed distance per year (m), η is the propulsion efficiency (often close to 0.1). In the present work we did not study the vessel ability to tow the gear at a higher propulsion efficiency, h_f is the diesel fuel energy equivalence (around 36 GJ/m^3).

The propulsion efficiency was roughly assessed from personal data and from the work of Prat et al. (2008). This efficiency is the ratio between the power required to tow the gear and the power delivered by the fuel consumption. The power for towing is the gear drag (29 KN $\pm$ 5 KN in Prat) by the towing speed (1.7 m/s $\pm$ 0.2 m/s) and the power delivered by the fuel consumption (693 KW $\pm$ 103 KW) is calculated using a fuel density of 0.762. In the case of Prat's study this efficiency is 7% $\pm$ 1%. By adding personal data we assess the efficiency at 10%.

The improvement in fishing gear in our present paper was carried out without impacting the quantity of fish caught per year (F). It is clear that the catching process is complex, anyway we propose here a simple model which links the quantity (F) on the swept volume per year by the trawl, on the fish distribution in the water volume and on the trawl catching efficiency. The swept volume per year by the trawl is the product of the mouth area of the trawl by the towed distance per year (L). The fish distribution in the water volume is generally close to the sea bottom for fish targeted by bottom trawls. In this work, we propose a simple modeling of fish distribution. The distribution is defined as a linear function of the depth above the sea bottom (in Fig. 3 the various distributions are depicted). The amount of fish caught by the trawl is the intersection of the mouth trawl and the fish distribution as shown in Fig. 4.

To summarize, the quantity of fish caught per year is the product of the annual covered distance (L) by the intersection area weighted by fish distribution (S_i) and the trawl catching efficiency (T_c). Here the trawl catching efficiency is expected not to be affected by the method of gear improvement. Under these

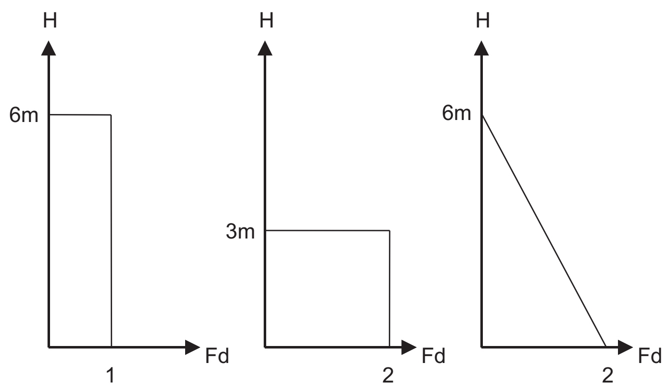

Fig. 3. Three distributions of fish density relative to the bottom are used.

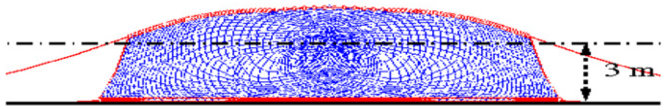

Fig. 4. Front view of a trawl. The fish entering the trawl is expected to be at the intersection area (S_i) between the mouth trawl and the fish distribution (here 3 m high between the two lines).

Table 1
Drag repartition between bottom trawl components. These figures come from modeling, which shows that most of the drag is due to the netting (Priour, 2009).

Cables (%)	7–8
Otter boards (%)	19–21
Netting (%)	60–66
Catch (%)	0–10
Ground rope (%)	4–5
Total (%)	100

conditions the fish caught per year is

$$F = S_i L T_c \tag{2}$$

F is the fish caught per year (kg), S_i is the intersection between the mouth area of the bottom trawl and fish distribution, weighted by fish distribution (m^2), L is the towed distance per year (m), T_c is the trawl catching efficiency (kg/m^3).

Gear improvement is intended to decrease the ratio between the fuel consumed and the fish caught. This ratio is calculated from the previous two equations:

$$\frac{V_f}{F} = \frac{D}{S_i}\frac{1}{\eta h_f T_c} \tag{3}$$

Since it is expected that the parameters η, h_f and T_c are constant, in other words, unaffected by the optimization process, the optimization objective function is the ratio D/S_i.

While it is acceptable to assume that η and h_f will not be affected by the optimization process, it is not the case for the catch per swept volume (T_c). For example a larger vertical opening due to optimization will probably increase the catch per swept volume for some species. But in this study we can accept a non-influence as a first hypothesis, as the trawl shape after optimization is not too different from the reference shape.

2.2.1. The trawl drag

In Table 1, the proportion of each of the trawl components that contribute to the overall drag are shown for some examples of bottom trawl. It is obvious that most of the drag is due to the netting. Because the drag is mostly due to the netting, optimization focuses only on the panel cutting in order to reduce the D/S_i ratio.

The FEM model described previously (Priour, 2009) calculates the drag and the swept area of trawls taking into account the following forces exerted on the structure:

- The inner tension in twines:

$$T_n = EA\frac{n-n_0}{n_0} \tag{4}$$

T_n: tension in twines (N),
E: modulus of twine elasticity (Pa),
A: twine section (m^2),
n_0: unstretched length of mesh side (m),
n: stretched length of mesh side (m).

- The drag force exerted on each twine of the net by the towing speed (Bessonneau and Marichal, 1998):

$$F = \tfrac{1}{2}\rho C_d DL(V\sin\theta)^2 \tag{5}$$

$$T = f\tfrac{1}{2}\rho C_d DL(V\cos\theta)^2 \tag{6}$$

F: normal force (N) to the twine. This expression comes from the Landweber hypothesis.
T: tangential force which comes from the Richtmeyer hypothesis,
ρ: mass density of water (close to 1025 kg/m^3),
C_d: normal drag coefficient (here 1.2),
f: tangential coefficient (here 0.08),
D: diameter of the twine (m),
L: length of the twine (m),
V: amplitude of the towing speed (m/s),
θ: angle between the twine and the towing speed (radian).

- The drag on the bottom (Folch et al., 2007):

$$F_c = CoefF_v \tag{7}$$

F_c: drag on the bottom (N),
F_v: vertical force on the bottom (N),
$Coef$: friction coefficient (here 0.5).

2.2.2. The mouth surface

In the numerical model the netting is modeled by triangular finite elements (Priour, 1999). The mouth area is calculated as the sum of the projection of each triangular element on the plane perpendicular to the towing displacement.

2.2.3. Fish distribution

Fish distribution relative to depth with respect to sea bottom has to be discussed with biologists and fishermen. This distribution displays where the fish encounters the gear. Three distributions were selected. They are defined by three parameters: the upper limit depth (h) with respect to sea bottom and the fish volumic density at h (dh) and at the bottom (db). We have two uniform distributions (for the first: $h=6$ m, $dh=db=1$; for the second: $h=3$ m, $dh=db=2$), whereas the last distribution has a linear variation ($h=6$ m, $dh=0$, $db=2$). In Fig. 3 the three distributions were chosen, so that they lead to the same total fish quantity, for example, the second distribution is twice denser than the first one but half the height above the sea bed.

2.2.4. Intersection of mouth area with fish density

The trawl mouth area is calculated by adding up the triangular elements perpendicular to the towing direction. This projection of triangular elements, which is a surface area (m^2), encounters the fish distribution. The intersection between this surface area and the fish distribution S_i quantifies a scalar proportional to the mass of fish caught for a tow of 1 m long. This intersection S_i is simply the product of the surface area by the density of fish at the triangular element depth.

2.3. Detailed example illustrating the optimization process

We detail below one SOT step. Starting from an example of a structure made up of two panels (Fig. 1) and quantified by the following vector of variables:

$$U_0 = [-40\ \ -40\ \ -40\ \ 5\ \ 0\ \ 5\ \ 0\ \ -10\ \ -35\ \ 0\ \ -35\ \ 20\ \ 0\ \ 20\ \ 0\ \ 0].$$

This vector begins by the number of meshes along the horizontal axis of the first node of the first panel, followed by the number of meshes along the vertical axis of the same node, followed by the second node of the first panel up to the last node of the first panel followed by the second panel and so on until we reach the last panel. The size of this variables vector is the number of nodes multiplied by 2 (the number of mesh coordinates for each node).

This variables vector is modified step by step until the best solution to minimize the objective function is found.

The modifications involved are applied to the vector components one by one in mesh units, leaving the other components unchanged and equal to their starting value. In addition, the modifications are applied with opposite signs successively on pairs of vectors. In the event of symmetry, which is generally the case, the modifications have to be symmetrically applied. In order to illustrate the method, we chose an arbitrary modification step of six meshes for the first panel and nine for the second one in the case of Figs. 1 and 2. Due to symmetry the four nodes on the symmetry plane are modified in only one direction, which means that the number of modifications is 24.

The 24 successive vectors are as follows (the modified variable is in bold and the non-modifiable variables due to symmetry are in italic):

$U_1 = [-\mathbf{34}\ \ -40\ \ -40\ \ 5\ \ 0\ \ 5\ \ 0\ \ -10\ \ -35\ \ 0\ \ -35\ \ 20\ \ 0\ \ 20\ \ 0\ \ 0]$ (see Fig. 2).

$U_2 = [-\mathbf{46}\ \ -40\ \ -40\ \ 5\ \ 0\ \ 5\ \ 0\ \ -10\ \ -35\ \ 0\ \ -35\ \ 20\ \ 0\ \ 20\ \ 0\ \ 0]$.

$U_3 = [-40\ \ -\mathbf{34}\ \ -40\ \ 5\ \ 0\ \ 5\ \ 0\ \ -10\ \ -35\ \ 0\ \ -35\ \ 20\ \ 0\ \ 20\ \ 0\ \ 0]$.

$U_4 = [-40\ \ -\mathbf{46}\ \ -40\ \ 5\ \ 0\ \ 5\ \ 0\ \ -10\ \ -35\ \ 0\ \ -35\ \ 20\ \ 0\ \ 20\ \ 0\ \ 0]$.

$\vdots$

$U_{22} = [-40\ \ -40\ \ -40\ \ 5\ \ 0\ \ 5\ \ 0\ \ -10\ \ -35\ \ 0\ \ -35\ \ 20\ \ 0\ \ \mathbf{11}\ \ 0\ \ 0]$.

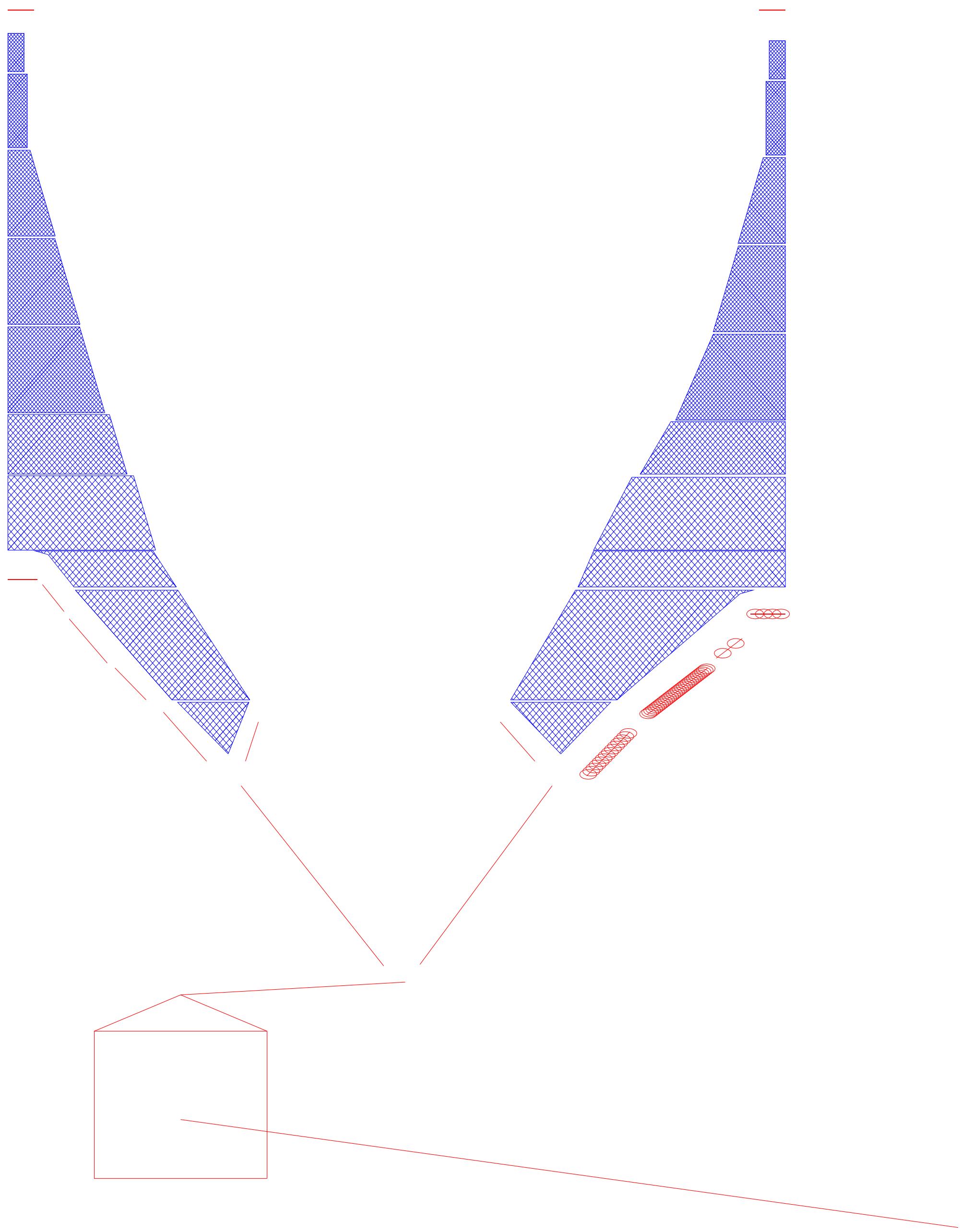

Fig. 5. Netting panels of the reference bottom trawl. Due to the symmetry of the trawl only half parts of the back and belly are presented. Due to the large number of twines only 1 twine out of 5 is drawn. The floats on the headline are displayed as well as the door (square).

$U_{23} = [-40\ \ -40\ \ -40\ \ 5\ \ 0\ \ 5\ \ 0\ \ -10\ \ -35\ \ 0\ \ -35\ \ 20\ \ 0\ \ 20\ \ 0\ \ \mathbf{9}]$.

$U_{24} = [-40\ \ -40\ \ -40\ \ 5\ \ 0\ \ 5\ \ 0\ \ -10\ \ -35\ \ 0\ \ -35\ \ 20\ \ 0\ \ 20\ \ 0\ \ \mathbf{-9}]$.

It is shown that only the first variable varies between U_0 and U_1; likewise for U_2. Only the second variable varies between U_0 and U_3; likewise for U_4. Up to last variable which varies between U_0 and U_{23}; likewise for U_{24}. For each vector the shape of the trawl is calculated as well as the objective function $\mathcal{F}$. This adds up to 25 objective function evaluations: $\mathcal{F}(U_0)$ for the reference (U_0) while the remaining 24 objective function evaluations correspond to the modifications (U_1 to U_{24}). From these 24 objective function evaluations the minimum is extracted and corresponds to U_n. If $\mathcal{F}(U_n) < \mathcal{F}(U_0)$, U_n is the kept design and used as the new reference U_0 with $\mathcal{F}$ the objective function. The process restarts from this reference: 24 modifications are applied and the objective function evaluations are calculated until $\mathcal{F}(U_n) \geq \mathcal{F}(U_0)$, $\forall n \in [1,24]$. The final optimized design corresponds to the last U_0.

2.4. The bottom trawl

The bottom trawl studied here is used on a research vessel (Study of factors affecting the variability of cod-end selectivity, 1998). Due to the symmetry of the trawl, only one half of the trawl design is displayed in Fig. 5. This one half design consists of 20 net panels. Each panel has a polygonal shape with multiple nodes which gives 134 variables. This trawl is used at 81 m deep with warps of 201 m and bridles of 36.6 m. The towing speed is 1.51 m/s.

2.5. Numerical parameters

Two main numerical parameters control the optimization process: the discretization size and the modification size. The discretization size is the size of the numerical elements used in the FEM model. The influence of these two numerical parameters have been analyzed in Priour (2009). The discretization size used in the optimization process is 2 m. Once the optimization process is carried out, a verification of the results with a discretization size of 0.5 m is done. The modification size is the quantity of meshes to add or remove from the panel: between Figs. 1 and 2 there is a modification of six meshes. In fact, in order to have the same proportion of modifications between each panel, we use a percentage ratio (PR). For example a 10% PR of a panel of 100 meshes wide will lead to a modification of 10 meshes. Only a few PR are used here: 64%, 32%, 16%, 8%, 4%, 2% and 1%. These values are chosen because they are significant but not too large.

2.6. Constraints

The optimization process is run with a number of constraints given below.

2.6.1. Panel discarding procedure

A few (10) rear panels (trawl back) have been excluded from the optimization process. The decision to discard rear panels from the optimization process was taken on the basis of two criteria: first of all, the low drag of the discarded panels and second, the relative strategic impact attributed to the panels.

Consequently, significant saving is achieved with respect to simulation time.

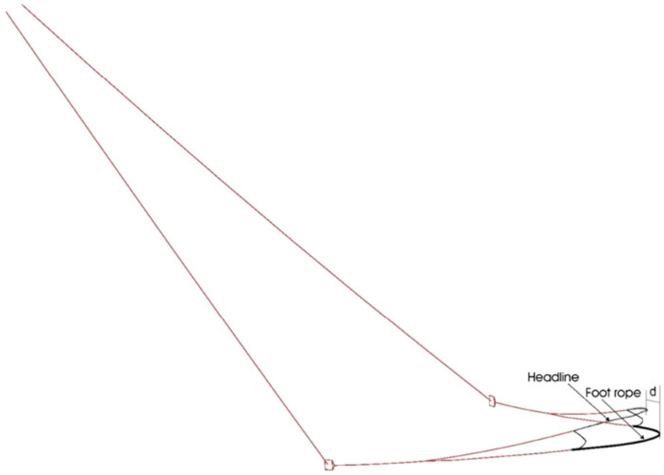

Fig. 6. Part of the trawl (the netting has been hidden). The warps are on the left, the doors are the squares. The foot-rope is behind the headline at a distance *d*.

2.6.2. Headline covering the foot-rope

For each combination of variables, some care should be exercised. Once the bottom trawl shape has been calculated, the foot-rope should be at least 3.5 m behind the headline in order to prevent fish escapement above the headline (Fig. 6).

This covering distance (d) is the horizontal length between the foot-rope and the headline. In the optimization process, this geometrical constraint is always checked by monitoring the minimum covering distance and whenever it is smaller than 3.5 m, the corresponding combination is rejected. The value of 3.5 m has been evaluated on the simulation of the reference trawl.

2.6.3. Contact with sea bottom

For some combinations of variables, the foot-rope could lose contact with the sea bottom and therefore the trawl catching efficiency may be reduced. For each combination case the contact is checked and if it is lost the corresponding combination is rejected. The contact is considered lost, when the distance between the bottom of the foot-rope and the sea bottom is larger than the radius of the foot-rope (0.15 m).

2.7. Potential time and money savings

The potential time and money savings generated by this optimization are evaluated on the following assumptions for both bottom trawls previously described: the reference and the optimized ones:

(i) The first hypothesis is that the quantity of fish caught per year with the optimized trawl is expected to be same as the reference trawl, that is to say, the same swept volume weighted by fish distribution. The trawl catching efficiency is expected to be constant between the reference and the optimized trawls.
(ii) The second hypothesis is that the efficiency of the engine and propeller equals 10%, the energy per liter of fuel equals 36 MJ/l and the fuel costs 0.6 €/l. Note that these values are considered acceptable for the year 2011.
(iii) The third hypothesis is that the trawling duration of the reference trawl is 21 h and 36 min per day for 260 days. This duration is calculated from standard weekly trips with each

haul consisting of 3 h of trawling and 20 min of hauling operations.

3. Results

3.1. Reference trawl

The reference trawl has been simulated. The calculated drag is 57 kN and the mouth area is 70 m^2, its intersection weighted with fish distribution at 6 m (3 m, linear) depth the swept area is 70 (129, 102) m^2 which gives a drag per intersection swept area equal to 811 (440, 558) N/m^2. The design of the reference trawl is displayed in Fig. 5 and the shape is in Fig. 7.

3.2. Optimization without taking into account fish distribution

In this case the objective function is the ratio of the drag over the swept width. The latter is the mean spread between the top and bottom wing tips. In Table 2 we display the objective function results and the vertical opening for each SOT percentage. Although the objective function reduction is good (10–19%), the vertical opening could be too small (2 m) leading to a reduction in trawl catching efficiency.

Such a small mouth height (2 m) is the reason for this current research work dealing with fish population distribution (uniform up to 3 and 6 m height and non-uniform linear variation up to 6 m height).

3.3. Optimization taking into account fish distribution

We chose for the ensuing optimization a different objective function given by the drag over the intersection area which is between the trawl opening area and the volume where the fish population is distributed.

With this objective function the SOT optimization begins with a large optimization percentage ratio (PR) of 64%. This PR value leads to good results for the objective function but large panel deformations whatever the fish distributions (constant up to 6 m high, constant up to 3 m or linear up to 6 m). The same conclusion was reached for PR of 32%, 16% and 8%.

In contrast, when the chosen PR is 4%, 2% and 1% the deformations are small while good results are simultaneously obtained for the objective function. We present those results where PR equals 2% which is a good compromise between the objective function reduction and the panel deformations.

They are displayed in three tables (Tables 3–5) with figures corresponding to a given fish distribution. In each table, the drag, the actual mouth surface, the intersection surface weighted with the fish distribution (S_i), the objective ($drag/S_i$) the vertical opening (*VO*: vertical opening at middle headline) and the horizontal opening (*HO*: mean wing ends spread) are presented.

Table 3
Optimization considering constant fish distribution up to 6 m. Main results of the optimization and considering modification size (PR) of 2%. These results are: objective function value ($Drag/S_i$), drag of the trawl, mouth area, weighted intersection swept mouth with fish distribution, vertical opening, horizontal opening. The results are for the reference and optimized trawls and the difference between the two trawls.

Objective values	opt6m with SOT at 2%		
	Ref	Opt	Diff (%)
Objective (N/m^2)	811	390	−52
Drag (kN)	57	57	0
Mouth surface (m^2)	70	173	147
S_i (m^2)	70	145	107
VO (m)	3.5	7.8	121
HO (m)	24.3	25.6	5

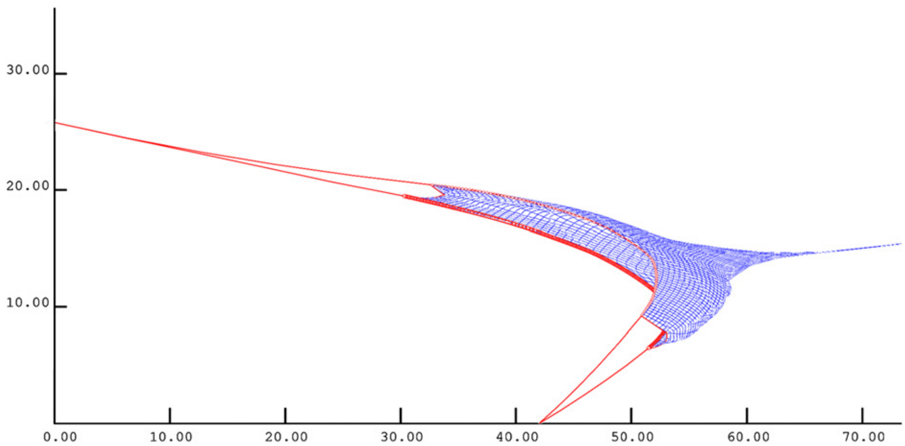

Fig. 7. 3D aspect of the reference bottom trawl. We display a zoom on the netting and only one twine out of 10 is drawn.

Table 2
Objective function is drag over swept width. Objective function results (in N/m and percents) and vertical opening for each SOT percentage ratio (PR) showing the overall decrease in mouth height with percentage ratio.

Measurement	Reference	Successive optimization tool (SOT)						
		1%	2%	4%	8%	16%	32%	64%
Objective (N/m)	2338	2086	2104	2054	1883	2069	1933	1946
Reduction (%)		−11	−10	−12	−19	−11	−17	−17
VO (m)	3.5	3.9	3.8	4.0	3.3	4.6	2.2	2.0

Regarding constant fish distribution up to 6 m high, the fuel consumption reduction is 52%. The corresponding 3D shape is shown in Fig. 8 and the design is shown in Fig. 9.

In the 3 m high case the fuel consumption reduction is 16%. The corresponding 3D shape is shown in Fig. 10 and the design is shown in Fig. 11.

In the non-uniform fish distribution 33% fuel consumption reduction is obtained. The corresponding 3D shape is shown in Fig. 12 and the design is shown in Fig. 13.

It can be seen in the designs (Figs. 9, 11 and 13) that only a few panels have been modified compared to the reference one (Fig. 5). It is also clear that the 3D shapes of the optimized trawls (Figs. 8, 10 and 12) are close to the reference one (Fig. 7).

Table 4
Optimization considering constant fish distribution up to 3 m. Main results of the optimization and considering modification size (PR) of 2%. These results are: objective function value ($Drag/S_i$), drag of the trawl, mouth area, weighted intersection swept mouth with fish distribution, vertical opening, horizontal opening. The results are for the reference and optimized trawls and the difference between the two trawls.

Objective values	opt3m with SOT at 2%		
	Ref	Opt	Diff (%)
Objective (N/m^2)	440	367	−16
Drag (kN)	57	54	−5
Mouth surface (m^2)	70	132	89
S_i (m^2)	129	147	14
VO (m)	3.5	5.9	68
HO (m)	24.3	26.4	9

Table 5
Optimization considering linear fish distribution up to 6 m. Main results of the optimization and considering modification size (PR) of 2%. These results are: objective function value ($Drag/S_i$), drag of the trawl, mouth area, weighted intersection swept mouth with fish distribution, vertical opening, horizontal opening. The results are for the reference and optimized trawls and the difference between the two trawls.

Objective values	opt-non-uniform with SOT at 2%		
	Ref	Opt	Diff (%)
Objective (N/m^2)	558	374	−33
Drag (kN)	57	55	−4
Mouth surface (m^2)	70	148	111
S_i (m^2)	102	146	44
VO (m)	3.5	6.5	86
HO (m)	24.3	26.5	9

However, the optimized trawls have a larger swept width (25.6 m, 26.4 m and 26.5 m) than the reference one (24.3 m). This means a potential increase in the fishing catch volume, leading to a decrease in the number of fishing trips.

3.4. Convergence speed

Table 6 details the execution times for the optimization procedure for the three fish distributions (6 m, 3 m and linear) for 2% PR as well as the total number of calculated trawls. It shows that the computation time for any given trawl iteration is about 13 s. The machine used is based on an 8 core (Intel Xeon^{TM}E5345 @2.33 GHz) architecture with GNU gcc-4 compiler running under Linux Ubuntu 8.04.

3.5. Potential time and money savings

The main results, in terms of time and money savings, for the bottom trawls (shape of the reference trawl in Fig. 7 and the optimized trawls in Figs. 8, 10 and 12) are displayed in Table 7. With the assumptions defined in the method section (constant swept volume intersection per year which is weighted by fish density in Table 7), the duration per year decreases by 135 days with the optimized trawl and the expected economy in fuel costs amount to 140 k€ per year with a constant fish distribution up to 6 m high. The duration per year decreases by 32 days with the optimized trawl and the expected economy in fuel costs amount to 44 k€ per year with a constant fish distribution up to 3 m high. The duration per year decreases by 79 days with the optimized trawl and the expected economy in fuel costs amount to 89 k€ per year with linear distribution.

4. Conclusion and discussion

In this study we report on energy efficiency optimization regarding bottom trawl design. The optimization approach developed in this study leads to a substantial improvement in terms of energy efficiency savings for bottom trawl (16%–52%). This significant improvement was achieved depending on the fish spatial distribution which is introduced in the objective function.

We have defined a very simple model for the catching process: the quantity of fish caught depends on fish distribution and trawl mouth area. In future work, this relation could be improved by taking into account fish behavior.

The SOT optimization method was modified in order to implement an alternative objective function given by the ratio

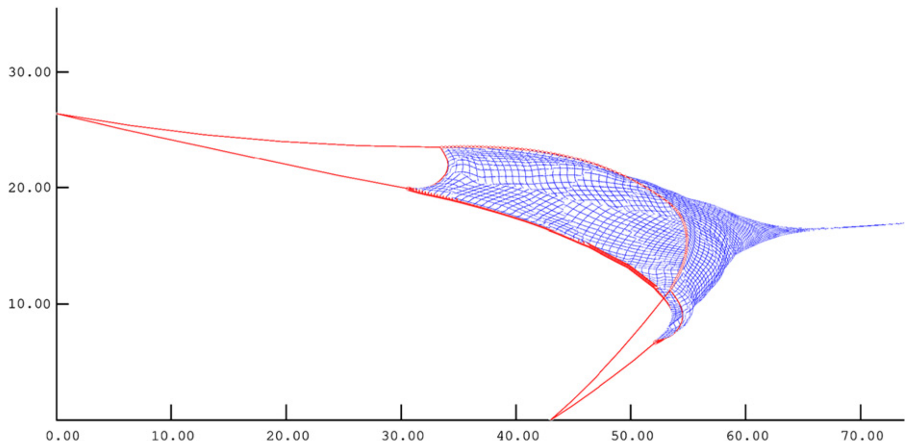

Fig. 8. 3D shape of the trawl optimized with SOT at 2% PR for a uniform distribution of fish up to 6 m high.

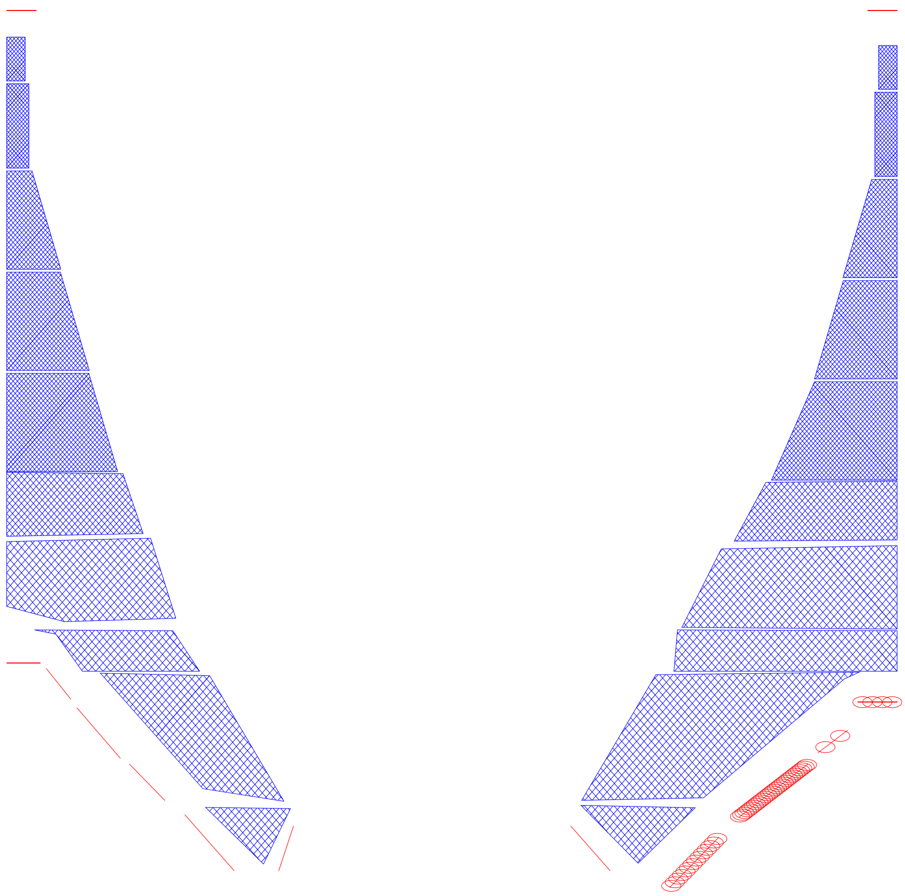

Fig. 9. Design of the trawl optimized with SOT at 2% PR for a uniform distribution of fish up to 6 m high.

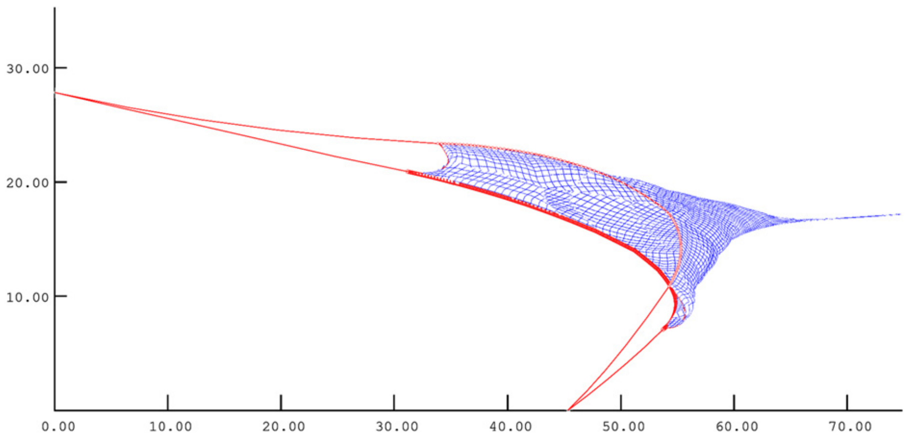

Fig. 10. 3D shape of the trawl optimized with SOT at 2% PR for a uniform distribution of fish up to 3 m high.

of the drag to the effective swept area S_i. This change was triggered by the fact that sometimes when using an objective function given by the ratio of drag to swept width, one may sometimes obtain a decrease in the trawl mouth height. This decrease could lead to a reduction in the amount of fish caught by lessening the volume of filtered water.

The objective function given by the ratio of drag to effective swept area S_i is equal to an intersection area weighted by fish distribution. This intersection area is between the trawl mouth area and the volume over which the fish population is distributed. Hence it depends on fish spatial distribution. Uniform (up to 3 and 6 m high) and non-uniform distribution (linear spatial variation up to 6 m high) were considered in this study.

As seen in the design figures (Figs. 9, 11 and 13) fish distribution impacts the optimized designs. Therefore it is of paramount importance to discuss such fish distributions with the biologists and fishermen.

Table 3 shows clearly a relatively large increase in the vertical opening. This could modify significantly the catch per swept volume for some species. This point must also be discussed with the biologists and fishermen.

Nevertheless, the effects of some modifications are identical whatever the fish distributions. It is the case of the headline bosom (mid-headline). It is shown in the three optimized designs (Figs. 9, 11 and 13) that optimization led to the same cutting. We could probably explain this by the fact that the piece of removed

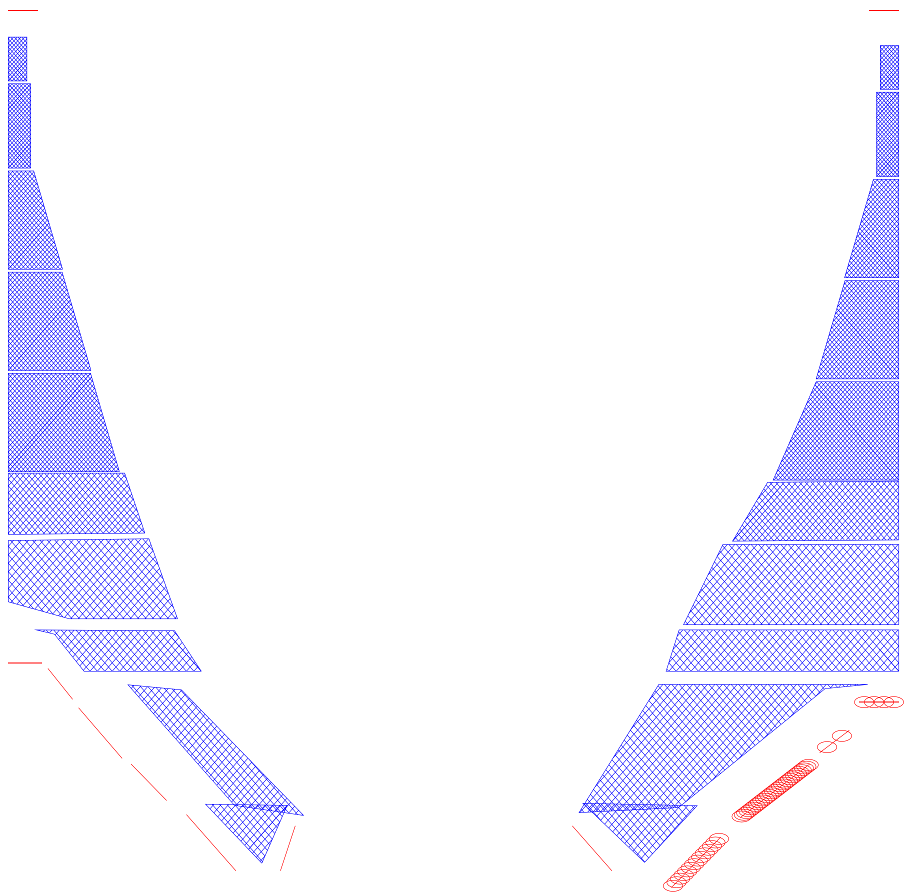

Fig. 11. Design of the trawl optimized with SOT at 2% PR for a uniform distribution of fish up to 3 m high.

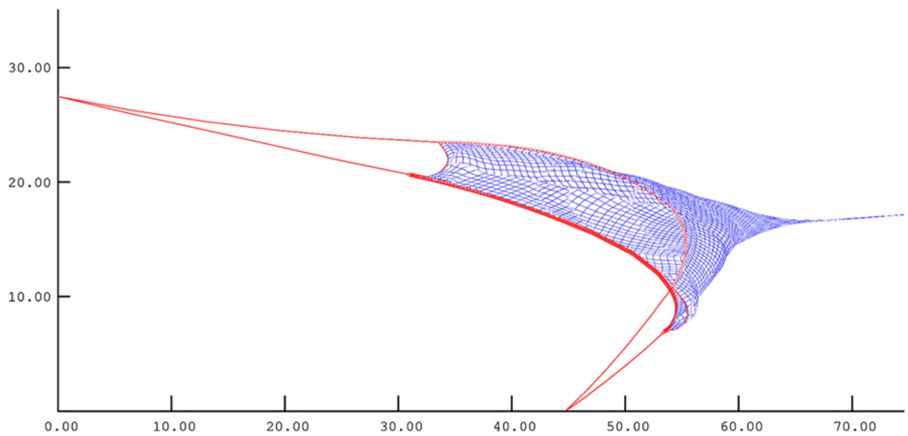

Fig. 12. 3D shape of the trawl optimized with SOT at 2% PR for a linear distribution of fish up to 6 m high.

netting generates an extra drag without increasing the mouth surface area.

It can also be seen in the three designs (Figs. 9, 11 and 13) that optimization sometimes leads to panel cuttings which are not straight. It is the case of the second panel of the belly in Fig. 13. This non-straight cut would be unacceptable to fishermen. This is why we should introduce new geometrical constraints on panel cutting in order to avoid non-straight cuttings, in accordance with the requests from fishermen.

The modification size amount (PR) cannot a priori be determined accurately, which is why optimization was carried out using PR values ranging from 1% to 64%. Once, all the results are collected the best is chosen in terms of energy improvement and design. Nevertheless this could lead to large modifications, in some cases, in a given set of panels regarding trawl design. This is one of the factors that should induce large geometric changes in panel design.

The algorithm used in this study converges by definition as mentioned previously, but it is not very stable: Table 2 shows that a variation in SOT percentage leads to a variation in objective function values. This means that each SOT percentage leads to a local minimum, otherwise each SOT percentage would lead to the same global minimum. The algorithm is not unstable because, as in Table 2, the reductions are in the same order of magnitude

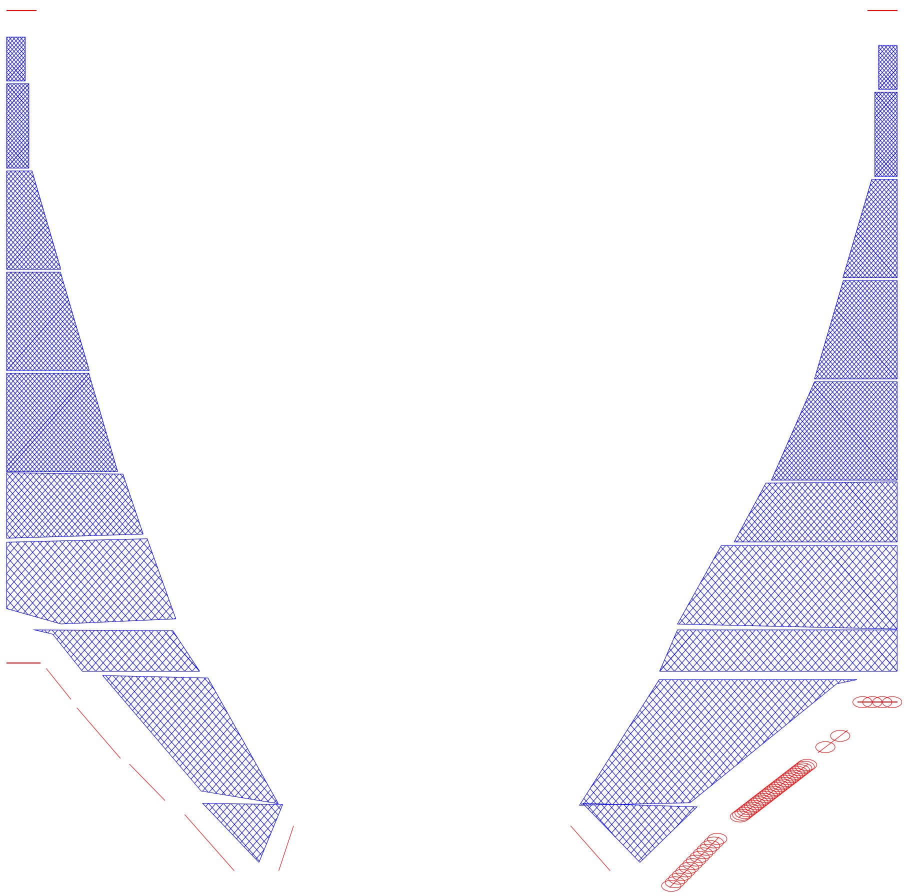

Fig. 13. Design of the trawl optimized with SOT at 2% PR for a linear distribution of fish up to 6 m high.

Table 6
Total optimization time versus trawl number for 2% percentage ratio for the three distributions: 6 m, 3 m and linear case.

Fish distribution	Successive optimization tool (SOT)	
Constant up to 6 m	Number of evaluated trawls	10 064
	Execution time	14 h 44 mn
Constant up to 3 m	Number of evaluated trawls	14 652
	Execution time	21 h 27 mn
Linear up to 6 m	Number of evaluated trawls	9324
	Execution time	13 h 39 mn

Table 7
Comparison of the reference bottom trawl with the SOT at 2% percentage ratio optimized in terms of time at sea and fuel cost for constant (6 m, 3 m) and linear fish distributions. The weighted swept volumes per fish distribution are identical.

Objective values	Reference			Optimized		
	6 m	3 m	Linear	6 m	3 m	Linear
Drag (kN)	57			57	54	55
Width (m)	24.3			25.6	26.4	26.5
Duration (days/y)	**260**			**125**	**228**	**181**
Distance (km/y)	30 529			14 726	26 799	21 195
S_i (m^2)	70	129	102	145	147	146
Volume (km^3/y)	2.1	3.9	3.1	2.1	3.9	3.1
Drag energy (MWh/y)	481			231	402	322
Fuel volume (m^3/y)	450			216	376	301
Fuel cost (€/y)	**269 764**			**129 703**	**225 321**	**180 724**

(10–19%). We hypothesize that this is due to the large number of variables which inhibits the possible exploration of all the combinations of the variables.

In order to avoid to be stuck in a poor local minimum, we have implemented large modifications (PR up to 64%), but we found a too large deformation of the design and such results with large modifications have not been kept.

Thus our future strategy will be to perform each optimization step while respecting a set of geometrical constraints. This will introduce a set of geometric boundaries, thus limiting the node excursion amplitude in each panel during each algorithm run. We call these constraints local in contrast with the global ones which are considered in large simulations involving the full structure of the trawl.

Tables 4 and 5 show a reduction in drag for optimized trawls. This reduction could lead to discussions with the fishermen regarding the opportunity to adjust the door surface areas or the propulsion efficiency. In this study these parameters are constant by hypothesis. Thus if these parameters (door surface areas or propulsion efficiency) must be included in the optimization process, and if the relationship between the drag and these parameters is known then it can be included in the modeling in future studies.

Acknowledgments

The authors would like to thank the European Fisheries Fund and the French Ministry of Agriculture and Fisheries for funding this field of research.

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